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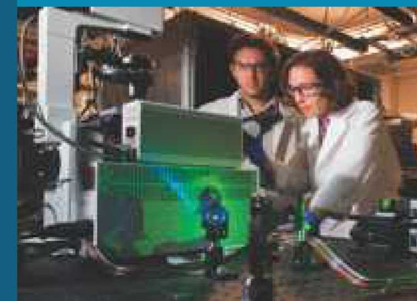

Optimization of Shaker Locations for Multiple Shaker Environmental Testing



IMAC 2019

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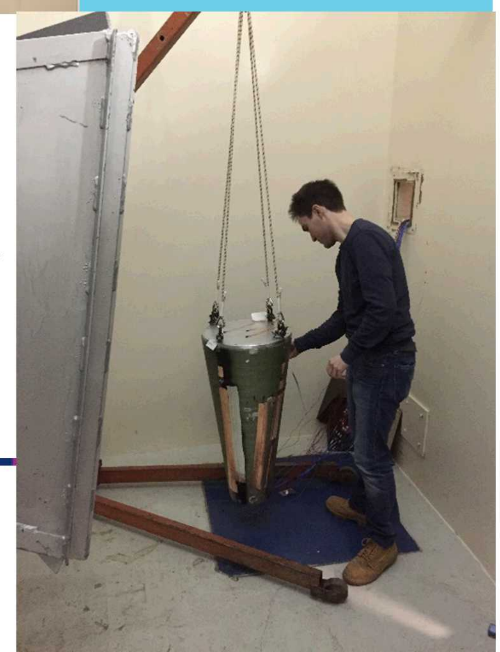

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Motivation for a better ground test method

- At IMAC in 2014, Daborn, Ind, Ewins and Roberts in the UK showed that vibrations induced at 13 locations on a scale model missile in a wind tunnel could be reproduced well with an approximate boundary condition and three modal shakers with multi-input multi-output (MIMO) control.
- The technique was named Impedance-Matched Multi-Axis Testing (IMMAT).
- IMMAT matching of multiple field responses is a huge improvement over what can be achieved with single axis shaker table.
- IMMAT power requirements are only a few percent of the single axis shaker power requirements.

Unanswered Multi-Shaker Testing Questions

- HOWEVER, we have not had technology to guide:
  - How many shakers are required for a particular test?
  - Where should the shakers be placed?
  - Can the shakers or amplifiers physically achieve the environment, i.e. will the test exceed the physical capabilities such as max output current / voltage / force / displacement?
- This work was focused on attempting to answer these questions.

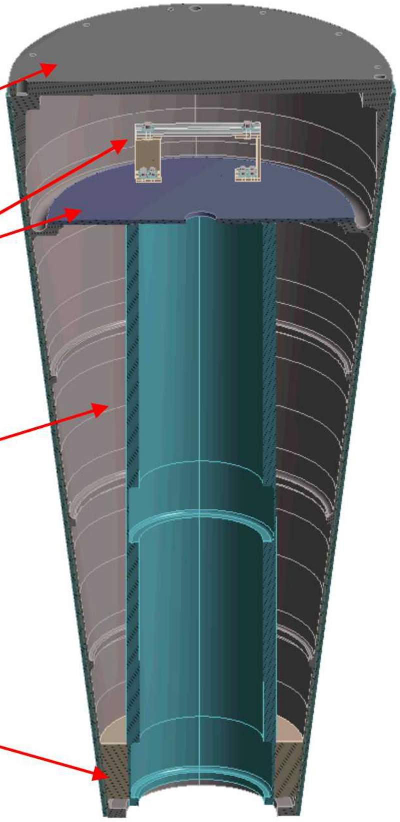
Approach to develop IMMAT test design

- Obtain a modal model of the test article with shapes at control dof and candidate shaker attachment dof.
- Obtain a shaker/amplifier model.
- Use substructuring to couple desired shakers to test article model.
- Use the model to calculate the output voltage required for each amplifier to achieve the control accelerations.
- Check other quantities to see if they are acceptable:
  - Shaker force
  - Shaker displacement
  - Amplifier output current
  - Control error
- Optimize the model appropriately (here we minimize amplifier output voltage).

Proof of concept Hardware for IMMAT test design - MATV

- The project proposed to prove the IMMAT test design using research hardware provided by AWE known as the Modal Analysis Test Vehicle (MATV) which would be tested in a field random acoustic environment. Then a designed IMMAT test would be run with multiple shakers to attempt to simulate the field accelerations.

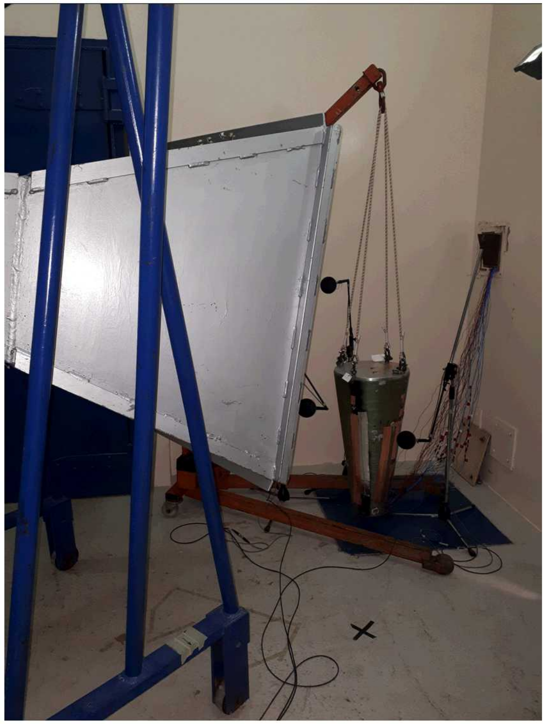
- MATV Description
  - One meter long
  - 47 kg
  - Composite wrapped on aluminum substrate cone
  - Large end aluminum cover plate
  - Aluminum internal flat component plate
  - Bracket called the Removable Component (RC) bolted to the internal component plate
  - Steel pipe bolted to the component plate
  - Foam support between pipe and cone at small end



Field Acoustic Test for MATV

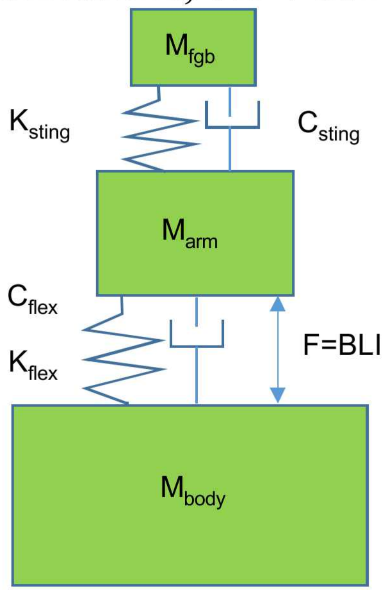
- A field acoustic test was run to 147 dB at the Institute of Sound and Vibration Research at Southampton University in a reverberant chamber with horn.

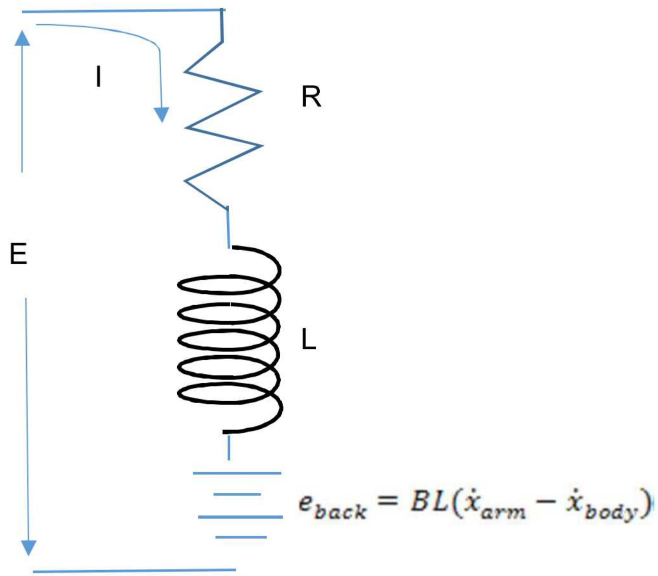
- MATV suspended by bungees in corner of chamber
- Horn
- 69 total accelerometer channels recorded



Shaker / Amplifier 4 dof Model

- As Tony Moulder and I began investigations to characterize a BEAK 1000 amplifier coupled with a LS-70 shaker, Phil Ind found a paper by Fox and Lang in the October 2001 Sound and Vibration magazine that modeled standard large laboratory shakers. With some small modifications, the 4 dof model of the modal shaker is shown below.





$$K = \begin{bmatrix} Ksting & -Ksting & 0 & 0 \\ -Ksting & Ksting + Kflex & -Kflex & -BL \\ 0 & -Kflex & Kflex & BL \\ 0 & 0 & 0 & R \end{bmatrix}$$

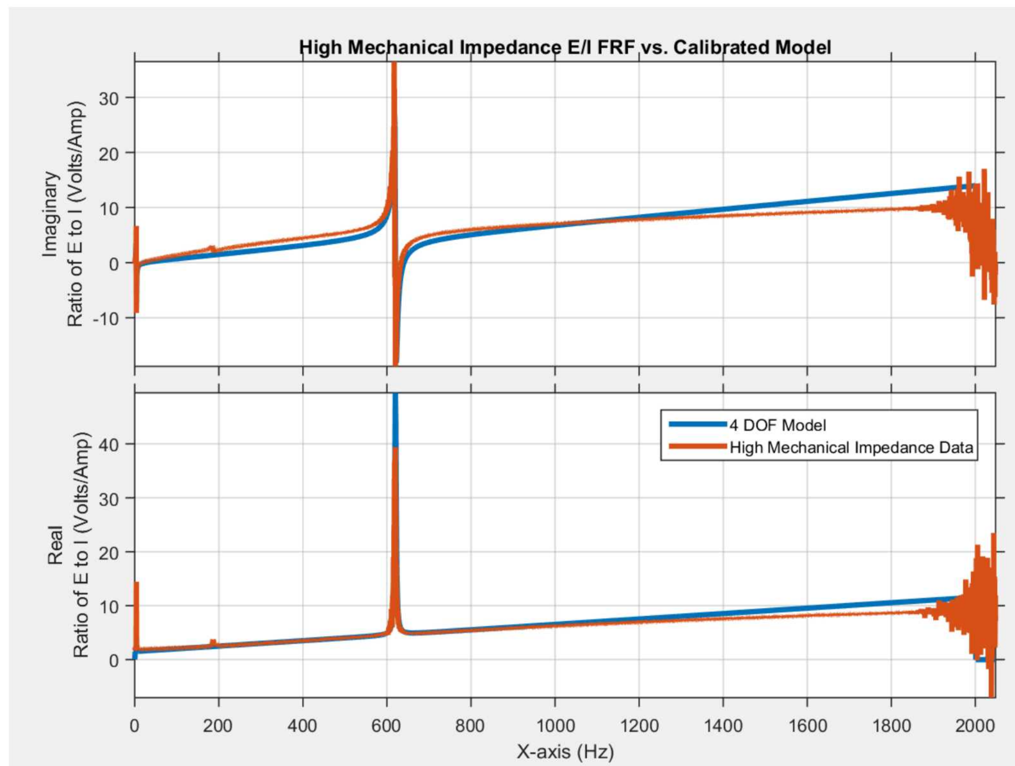
$$C = \begin{bmatrix} Csting & -Csting & 0 & 0 \\ -Csting & Csting + Cflex & -Cflex & 0 \\ 0 & -Cflex & Cflex & 0 \\ 0 & BL & -BL & L \end{bmatrix}$$

$$M = \begin{bmatrix} Mfgb & 0 & 0 & 0 \\ 0 & Marm & 0 & 0 \\ 0 & 0 & Mbody & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[K + j\omega C - \omega^2 M]\begin{Bmatrix} x_{fgb} \\ x_{arm} \\ x_{body} \\ I \end{Bmatrix} = \begin{Bmatrix} F_{fgb} \\ F_{arm} \\ F_{body} \\ E \end{Bmatrix}$$

Calibrating Shaker / Amplifier 4 dof Model

- The model can be calibrated against a high impedance test – M's were measured, R was published.
- K_{flex} and K_{sting} calibrated to achieve frequency match.
- Magnetic field, Inductance and C_{flex} calibrated to achieve amplitude match



System Modeling and Control Equations

- Substructuring theory according to deKlerk, Rixen, Voormeeren primal method beginning with uncoupled equations of motion of FE MATV model, a shaker/amplifier model and a constraint equation.

$$\left[\begin{bmatrix}\omega_{MATV}^2 & 0\\ 0 & K_{S/A}\end{bmatrix} - \omega^2\begin{bmatrix}I_{MATV} & 0\\ 0 & M_{S/A}\end{bmatrix}\right]\begin{Bmatrix}q\\ x\end{Bmatrix}=\begin{Bmatrix}F\\ V\end{Bmatrix}$$

$$x_{attachment}^{MATV} - x_{attachment}^{ForceGage} = 0$$

- The constraint can be written

$$\tilde{B}\begin{Bmatrix}q\\ x\end{Bmatrix} = \{0\}$$

$$\begin{Bmatrix}q\\ x\end{Bmatrix} = \tilde{L}\{\eta\}$$

$$\tilde{L} = null(\tilde{B})$$

- Coupled equations are then

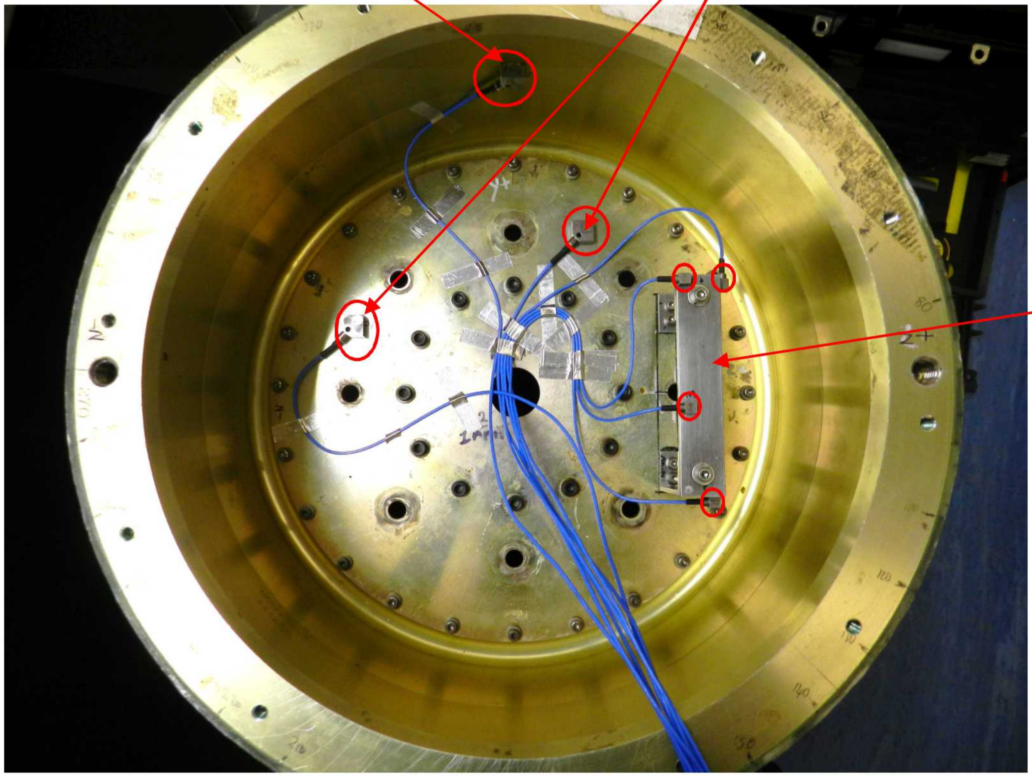
$$\tilde{L}^T\left[\begin{bmatrix}\omega_{MATV}^2 & 0\\ 0 & K_{S/A}\end{bmatrix} - \omega^2\begin{bmatrix}I_{MATV} & 0\\ 0 & M_{S/A}\end{bmatrix}\right]\tilde{L}\{\eta\}= \tilde{L}^T\begin{Bmatrix}F\\ V\end{Bmatrix}$$

- The control equation calculates voltage required for least square fit of control accel PSDs

$$S_{VV} = H^+S_{xx}H^{T+}$$

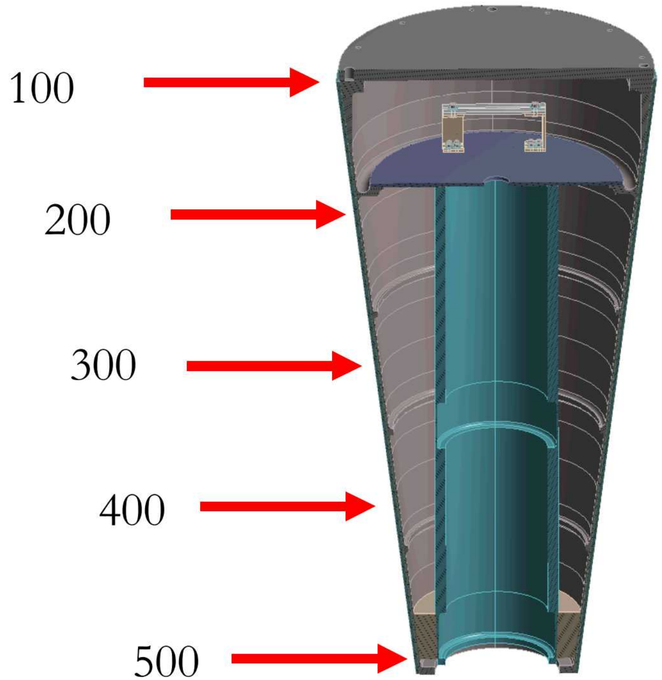
MATV Control Accel Locations

- 14 control accelerometer dof were chosen either on the RC or triaxial locations at typical mounting locations for a component



Shaker Candidate Locations

- 34 candidate shaker locations were chosen to optimize to achieve an achievable IMMAT test to match the target cross spectra.
- Input normal to the cone, 5 axial stations, 0,15,30,45,75,90 degrees at each station
- 2 axial inputs at each end.
- All were logistically feasible individually.

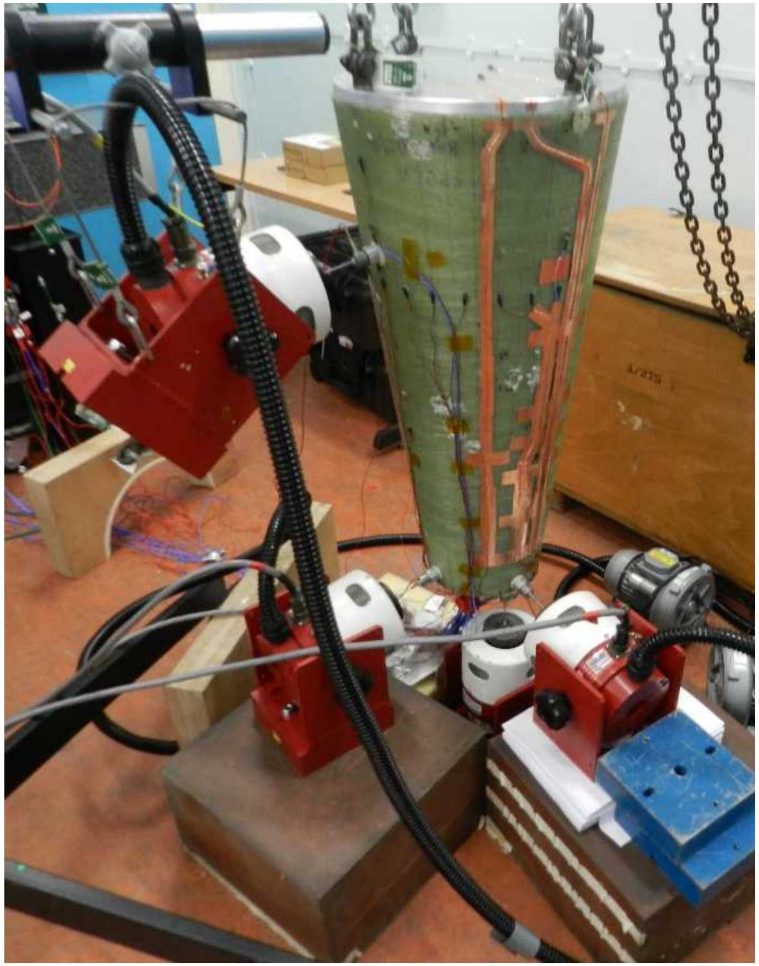


Shaker Optimization to minimize sum of Amplifier Output Voltages

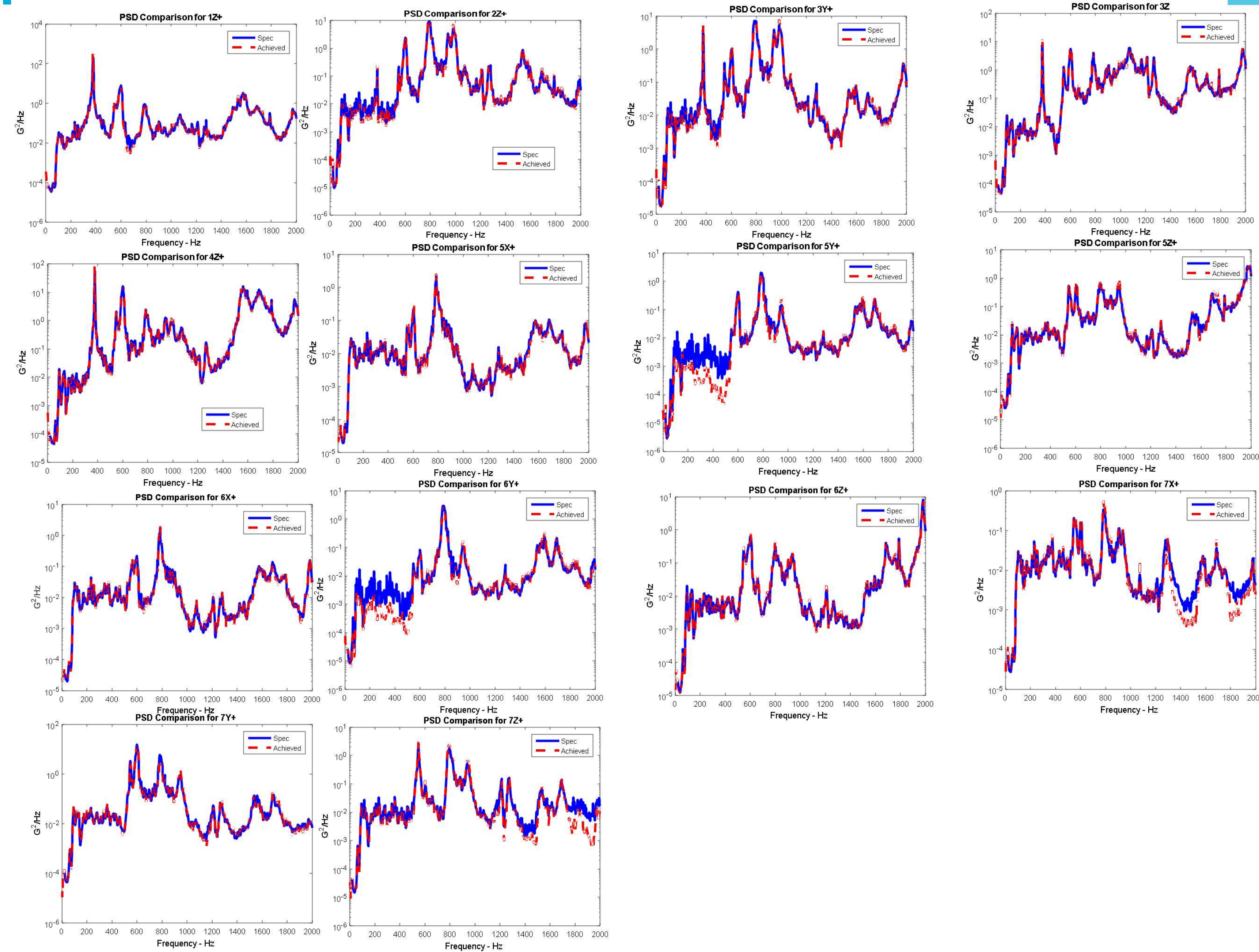
- Optimize the best shaker to add to whatever is the existing set
- Can minimize whatever quantity you like (force, voltage, current, control error, etc.)
- Physical Limit is 85V
- Here I choose to minimize the sum of Amplifier Output Voltages
- First shaker
  - Worst shaker 301Y- with 265 Volts
  - Best shaker 601X+ with 37 Volts, dBerr = 18,
- Second shaker
  - Best shaker 506Y- with [30 33 Volts], dBerr = 8.7
- Fourth shaker
  - Best shaker 204Y- with [33 24 29 50 V], dBerr = 4.7
- Sixth shaker (Blows Up!)
  - Best shaker 302Y- with [1073 6456 12300 27200 10900 30900V], dBerr = 3.1

Final Optimization Shaker Locations

- Logistics were better to put axial shaker on floor instead of hanging as 601X+ required.
- Final shakers were 501Y- 603X- 506Y- 206 Y-



IMMAT Test Results of LMS Control – Blue is Target, Red is Achieved



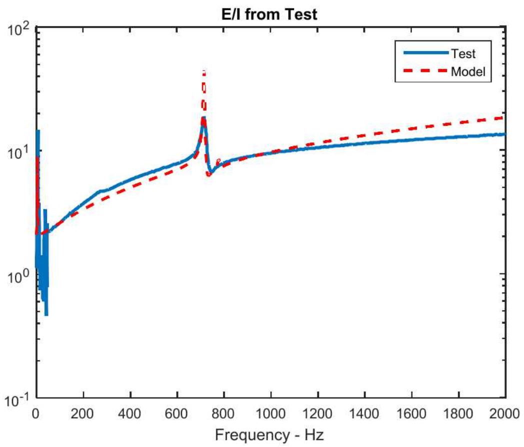
Conclusions

- Excellent control produced from optimization of 4 shakers to minimize amplifier voltage output
- Fewer shakers required than I thought would be needed
- More shakers are not always better
- We had enough voltage headroom to go to +3dB on target acceleration response PSDs

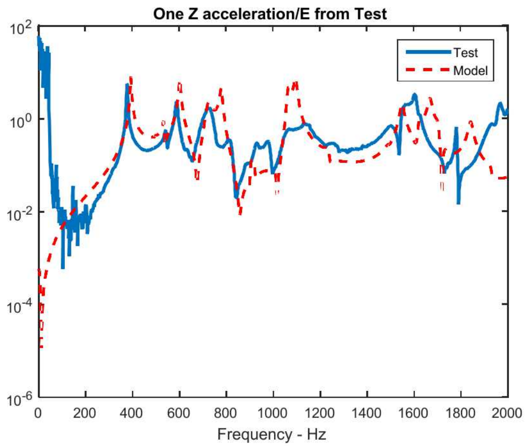
Backup Slide

Single Shaker / MATV Validation of Substructure Model

- To validate the combined shaker/amp + MATV model, AWE hooked up one shaker as shown in the picture.
- After minor calibration adjustments, some of the FRF quantities from the model and test are shown below. (Blue is measured and dashed red is model)



Voltage/Current



Response on RC Acceleration/Voltage

Predicted voltage error especially for most compliant shaker

- Final shaker were 501Y- 603X- 506Y- 206 Y-
- [26 34 25 74 V] [4 3 2 6 Amps] [102 102 52 102 N] 5.5 dBerr
- Actual voltage to run test was [31 22 21 29]
- The BIG MISS was on 206Y- : On further examination, high frequency modes above 2000Hz had residual flexibility that added a lot of response in the actual system. We did not include the high frequency modes above 2000 Hz. MORAL OF THE STORY – INCLUDE HIGHER FREQUENCY MODES (maybe twice the bandwidth)